Influence of creep on water pressure measured from borehole tests in the Meuse/Haute-Marne Callovo-Oxfordian argillites

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INFLUENCE OF CREEP ON WATER PRESSURE MEASURED FROM BOREHOLE TESTS IN THE MEUSE/HAUTE-MARNE CALLOVO-OXFORDIAN ARGILLITES

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Abstract :

Porewater pressure is an important parameter for use in safety assessment of underground waste disposal. In order to measure porewater pressure in the Callovo-Oxfordian argillites, Andra has performed several in-situ tests, which consist in measuring time-evolution of water pressure in an almost closed chamber. This was accomplished using an in-place pressure sensor coupled with an electromagnetic transmission device (called an EPG probe). The measured values show a small hydraulic overpressure (0.1 MPa) compared with the estimated value at the corresponding depth. In the framework of a scientific cooperation agreement between Andra and Ineris, a study was undertaken to examine whether all or a part of this overpressure could be attributed to the hydro-mechanical coupled processes linked with the creep of argillites and the stress relaxation in the experimental measuring chamber-nearby. In the whole, the numerical results were in good agreement with the measured results. Poroviscoplasticity can explain the increasing pressure in the borehole. The measured overpressure can be reached with adequate viscoplastic model parameters.

Keywords : numerical modelling, hydro-mechanical, porous, waterflow, creep, porewater

1. Introduction

ANDRA has over several years performed in-situ monitoring of Callovo-Oxfordian argillites in order to provide the required data for assessing the feasibility of a deep geological waste repository in this type of geologic media.

In this regard, ANDRA has performed water pressure measurements in several boreholes in the Callovo-Oxfordian argillites at different depths (about 420, 443 and 533 m). This is achieved using an in-place pressure sensor coupled with an electromagnetic transmission device called EPG probe, in which the water pressure is continuously monitored as it evolves naturally with time until a steady state is reached. Pore pressure measured in-situ at a given depth in this geology increases with time, and on achieving steady-state shows a overpressure (a value greater than expected at the depth of the sensor). In all cases this overpressure is small and does not exceed 0.1 MPa.

Laboratory tests have been performed on several Callovo-Oxfordian argillites samples and they show that this material exhibits a time-dependent behavior that is well described by Lemaitre viscoplastic model without any threshold. In other words, the behaviour of the argillites is time-dependent and strongly non-linear, being a function of the intensity of the deviatoric stress. The material creeps while deviatoric stress is not zero.

The scope of this study is to investigate whether this viscoplastic behaviour may explain the measured overpressure in the boreholes.

The geomechanical problem characterised by a borehole in a saturated argillite is clearly a coupled or hydro-mechanical problem (Wang, 2000). Porewater pressure evolution leads naturally to changes in the effective stress field values until the steady state is reached. However, due to the very significant viscosity of the rock, there are two interacting processes that act in opposing directions. These are the inflow or outflow of water within the borehole and the evolution in time of the borehole wall due to the viscoplastic strains.

In order to understand the meaning and the origin of the water overpressure, several numerical computations have been done. This was principally achieved with FLAC^{2D} software, complementary computations were made using a finite element code (VIPLEF).

Due to the size of the EPG probe and its position, the hydro-mechanical computations were performed on a reduced size problem and assuming axisymmetric conditions. It is shown numerically and analytically that in cases where the rock behaviour is poroelastic or if the mechanical behavior is not coupled with the hydraulic behaviour that the measured overpressure is not linked to the borehole creep. Moreover within a saturated viscoplastic media, the steady-state can only be reached when the boreholes void space is totally closed.

2. Context

The figure below shows the geological formations examined and the position of EPG probe inside these argillites, for the monitored site, located in Northeastern France (Fig. 1).

The three EPG sensors are located at 419.23 m, 442.60 m and 532.83 m depth respectively. The corresponding hydraulic heads are respectively equal to 400 m, 423.1 m and 514 m. The water pressure inside these boreholes has been monitored since 1996, 2002 and 2004 respectively.

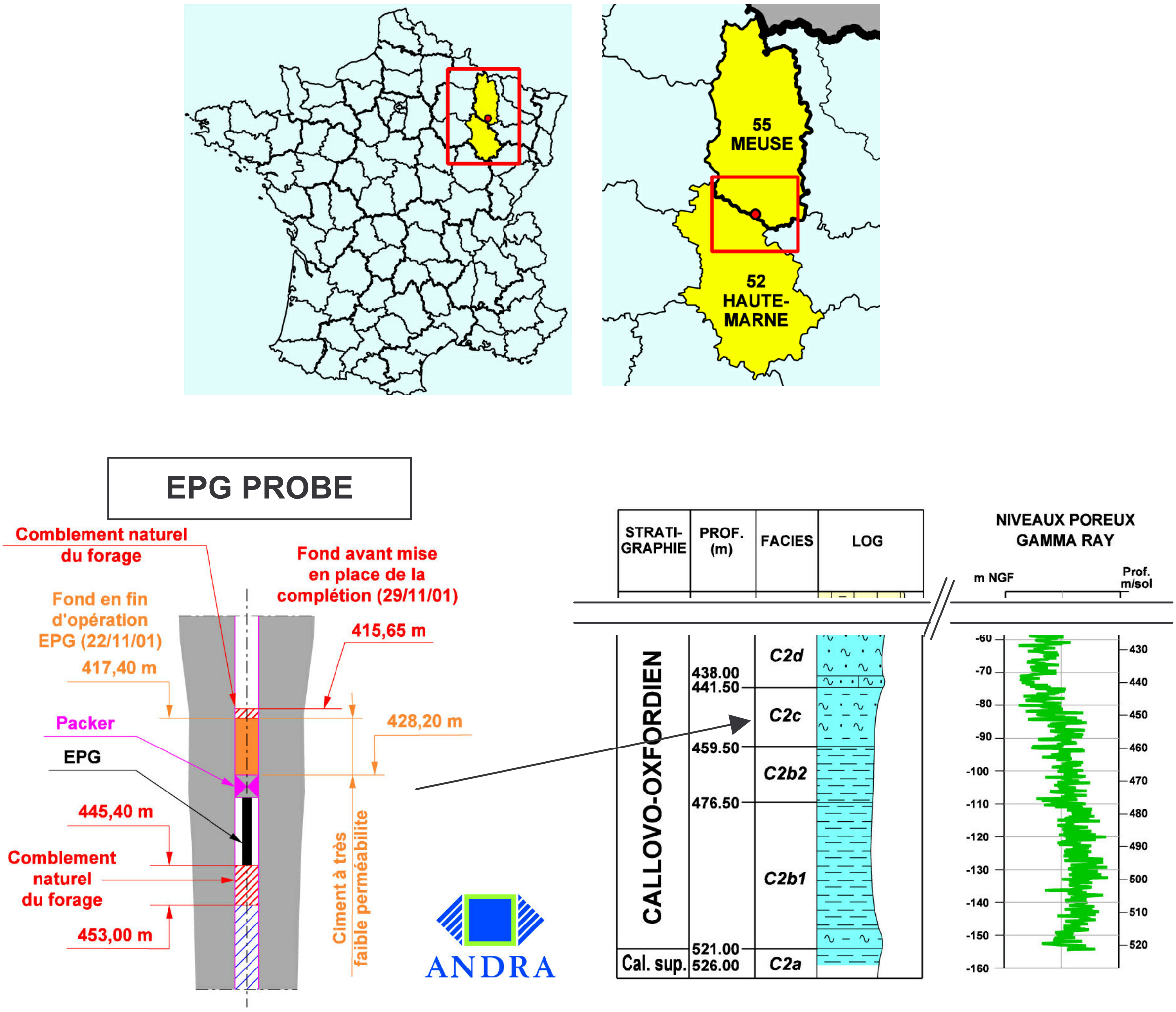

Figure 1 : Example of stratigraphic-log, gamma ray and situation of the EPG probe

3. Assumptions of the numerical modelling

This study is intended to provide an accurate numerical simulation that considers the different steps of the experiment (the drilling history , the geometry of the device and boundary conditions). All the currently recognized mechanisms involved, before, during and after the EPG probe installation are taken into account. The model used for the computation is depicted in figure 2.

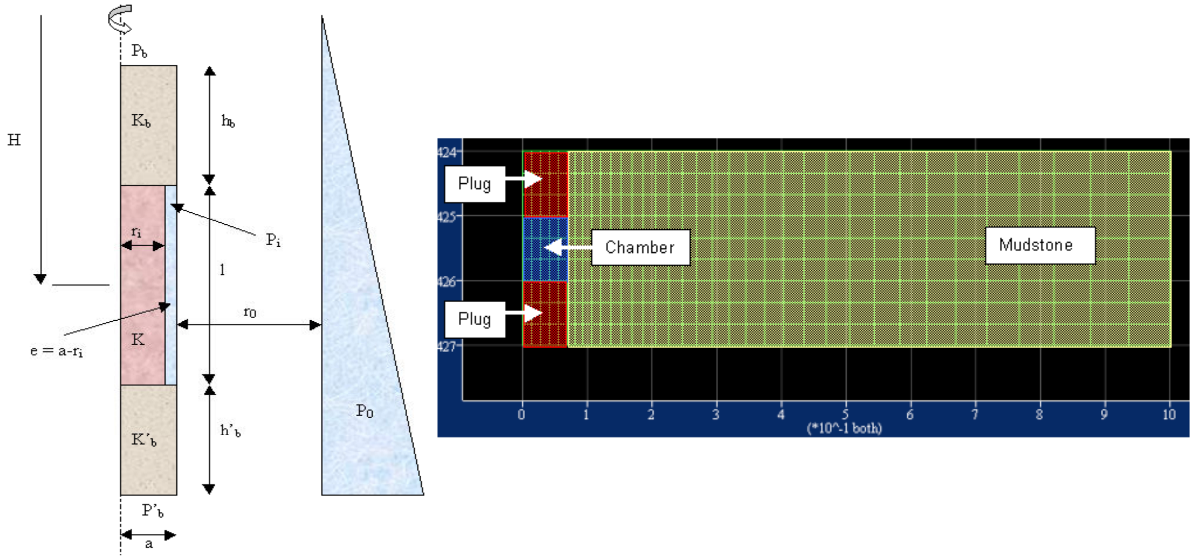

Figure 2 : Geometry and boundary conditions of the problem (left) and for FLAC^{2D} model (right) in axisymmetric conditions.

Lemaitre's constitutive model (Lemaitre, 1988), (a viscoplastic creep model), is used without any threshold in order to describe the time-dependent behavior of Callovo-Oxfordian argillites. The hydraulic behavior is also time-dependent, but all hydraulic and mechanical properties are assumed to be constant. This means that the damaged zone adjacent to the borehole walls is ignored in this model. In fact, it is known that within a damaged zone, the permeability may increase, however because of the small size (diameter) of the boreholes, the extension of the damaged zone is assumed to be very limited. Based on this assumption of a very limited region of disturbance the assumption of constant permeability is justified. In order to justify this several numerical elastoplastic modeling exercises have been performed using different values for the permeability in the plastic zone. No significant differences (less than 1%) were observed for the waterflow and the mechanical responses. No investigation were performed locally (in the plastic zone) to measure the effect on porewater pressure.

The numerical computations have been performed assuming a perfectly saturated soil. The hydro-mechanical problem is assumed to be independent of the temperature gradient within the soil (The temperature et le EPG cell level is about 23 Celsius degree) Let us recall that this study focuses on the competition between two associated phenomena: the wall closing associated with rock creep which leads to an increase of the water pressure in the chamber (or cell), and the water outflow-inflow from this water cell leading to the changes in the borehole pressure applied to the wall and therefore controlling the displacement of the wall.

The constitutive model, used to describe the argillite behavior is the Lemaitre model (Lemaitre, 1988) (also known as Menzel-Schreiner model) expressed in rate form as follows:

$$\frac{\partial \boldsymbol{\varepsilon}^{vp}}{\partial t} = Ae^{\left(\frac{-B}{T}\right)}\left(\frac{\sigma_{eq}}{\sigma_0}\right)^{\boldsymbol{n}}\left(\varepsilon_{eq}^{vp}\right)^{\boldsymbol{m}}\frac{\partial \sigma_{eq}}{\partial \boldsymbol{\sigma}} \qquad 1$$

Where $\boldsymbol{\varepsilon}^{vp}$ is the second order vicosplastic strain tensor, $\boldsymbol{\sigma}$ the Cauchy stress tensor, σ_{eq} the Von Mises equivalent stress ($\sigma_{eq} = \sqrt{\frac{3}{2}\boldsymbol{S}:\boldsymbol{S}}$) where $\boldsymbol{S}$ is the deviatoric stress tensor $\left(\boldsymbol{S} = \boldsymbol{\sigma} - \frac{tr(\boldsymbol{\sigma})}{3}\mathbf{I}\right)$. The hardening parameter is the equivalent viscoplastic strain defined as $\varepsilon_{eq}^{vp}\left(\varepsilon_{eq}^{vp} = \sqrt{\frac{2}{3}\boldsymbol{\varepsilon}^{vp}:\boldsymbol{\varepsilon}^{vp}}\right)$. The stress σ_0 is the reference stress value (1 MPa), and finally T is the temperature in Kelvin. It should be remembered that for this exercise the viscoplastic behavior of the argillites are assumed to contain no deviatoric stress threshold.

4. Results of the numerical computations

The main numerical modeling results that are depicted in figures 3 to 6 show the anticipated evolution of water pressure at the location of the borehole EPG sensor. This is a numerical simulation of the field installation, water pressure rate in the EPG cell, radial displacement at the cell or chamber wall and radial displacement rate of the wall. They show that the classical interpretation of pressure measurements (water flow uncoupled or independent of the rock mechanical behavior) does not lead to any prediction of porewater overpressure. The same conclusion is found if water flow is coupled with a purely elastic mechanical behavior. In the presence of creep however, the water pressure in the chamber reaches a higher value with respect to the pressure estimated at a given depth. This overpressure value (0.1 MPa) is very small comparing the expected water pressure value (about 4 MPa). This difference porewatrer pressure is about 2 %. This small influence on the calculated porewater pressure is mainly due to the very small size of the chamber, and also to the very limited creep of the argillites.

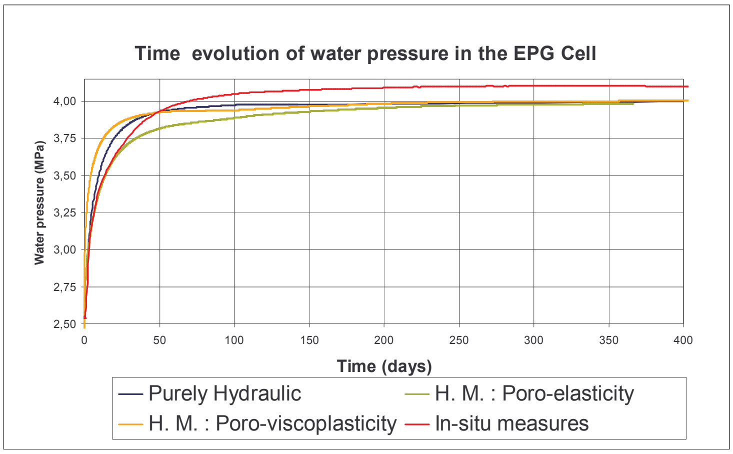

Figure 3: Water pressure evolution within the chamber: experimental data and numerical results.

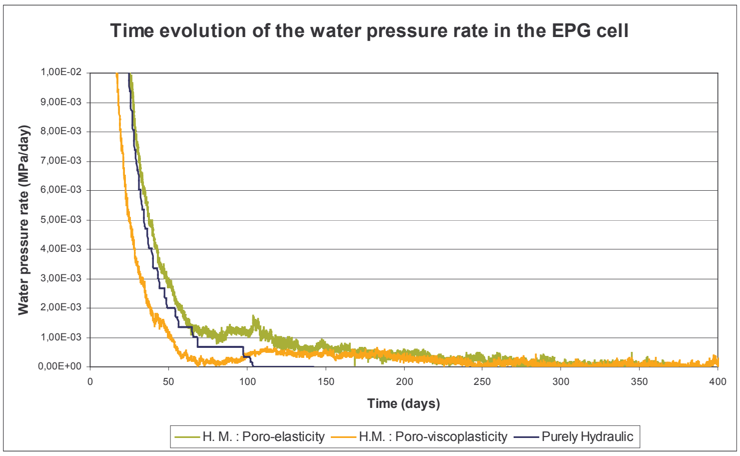

Figure 4: Water pressure rate evolution within the chamber.

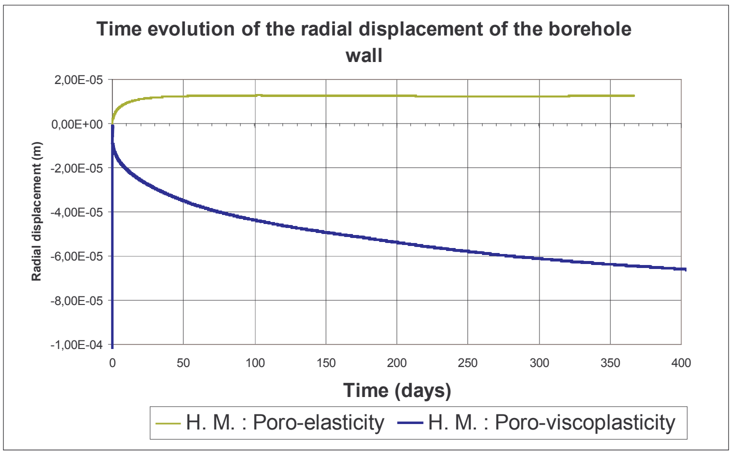

Figure 5: Time evolution of the radial displacement of the borehole wall.

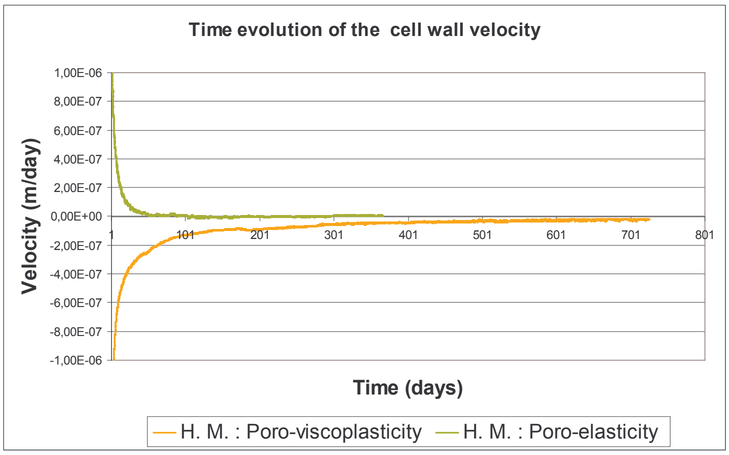

Figure 6: Time evolution of the radial displacement rate of the borehole wall.

As outlined above, all the field execution steps were taken into account in the modeling. In poroelasticity framework, the argillite is assumed to obey to an isotropic linear elastic constitutive model. During the excavation of the borehole, the rock deformed instantaneously (elastically) due to the stresses change near to the probe, leading to a reduction in the borehole radii or volume. After this step, the EPG probe and the two plugs are put in place. Water flows towards the probe, due to the gradient of the water pressure until steady-state is reached. During this transient state the water pressure inside the probe increases resulting in an increase of the chamber volume. No overpressure is obtained numerically (Kazmierczak, 2004).

In the viscoplasticity framework, the argillite is assumed to obey to the Lemaitre viscoplastic (without any threshold) constitutive model. During the excavation stage the rock is first deformed instantaneously (elastically) leading to a reduction in the borehole volume. The deformation of the borehole will continue following the initial elastic response due to the existence of deviatoric stress. Then the EPG probe and the two plugs are put in place. Water flows towards the probe. In contrast with the above elastic model, the rock is deformed in this case leading to a decrease in the borehole volume. This phenomenon will continueuntil the void space of the probe is totally closed, this requires a very long time since the material is very viscous. In such a case, the steady state is characterised by the closure of the void of probe. In the short term, the wall displacement caused by the argillite creep generates excess water pressure in the isolated sections of the borehole. This pressure build-up is linked to the probe volume reduction. The consequence is an outflow of the water from the borehole wall. At some time following installation, the viscoplastic strain rate decreases to a very low rate but at the same time the water inflow rate changes due to the water pressure gradient. The effect of water flow within the EPG probe, will also reduce the displacement rate of the wall as expected and demonstrated by numerical computation (Kazmierczak, 2004).

5. Some analytical evidences

Let us consider an initial homogeneous isotropic stress state at the considered depth H, $\sigma_o \underline{\underline{I}} = -\rho g H \underline{\underline{I}}$. The rock is assumed to be homogeneous and have a uniform density ρ. The sign conventions are the following: compression stress is taken negative and the water pressure is positive.

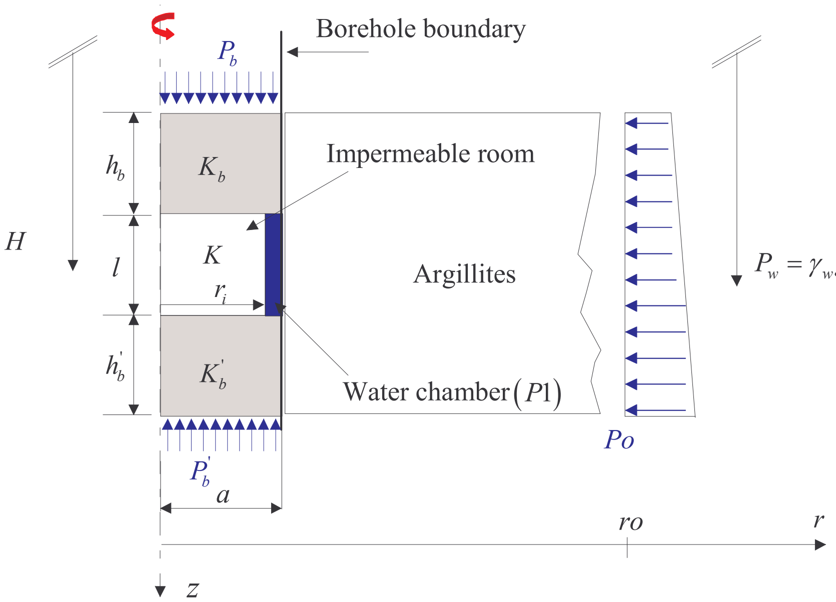

Figure 7: Schematic representation of the cell, the plugs in the well.

The porewater pressure, at the radius $r = ro$ is assumed equal to Po. This assumption is imposed in order to reach a hydraulic steady-state at a finite time (which cannot be obtained numerically in an infinite media with a cylindrical cavity).

As the chamber length is much larger than the water chamber thickness (Fig. 7) and due to the sizes ratios $(a - r_i)/l << 1$ and $(h_b + l + h_b^{'})/H << 1$ the plane strain condition can be assumed with respect to Z direction. Water mass balance in the water chamber leads, in polar co-ordinate, to the following equation:

$$\frac{\dot{P}_1}{K_w}\left[1-\left(\frac{r_i}{a}\right)^2\right]+2\rho_0\frac{\dot{u}}{a}+\frac{2\rho K}{a\eta}\left[\frac{\partial P}{\partial r}\right]_a+\frac{1}{l}\left[\rho_b\frac{K_b}{\eta}\frac{P_b-P_1}{h_b}+\rho'_b\frac{K'_b}{\eta}\frac{P'_b-P_1}{h'_b}\right]=0 \qquad 2$$

where P_1 is the water pressure in the cell, η the water viscosity, $\rho_b, \rho_b^{'}$ the plugs density, $K_b^{'}$ and K_b the plugs permeability. The different variables are depicted in figure 7. The dot stands for the time derivative and $\dot{u}$ denotes the radial displacement rate of the chamber wall.

Now consider, in a porous medium with constant permeability and viscosity, the axisymmetric form of the fluid (water) continuity equation:

$$\frac{1}{M}\frac{\partial P}{\partial t} + b\frac{\partial \varepsilon_v}{\partial t} = \frac{K}{\eta}\left(\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r}\right) \qquad 3$$

Where P is water pressure, M the Biot modulus, b the Biot coefficient and ε_v the volumetric strain. When the steady-state is reached, all time derivative of the above equations vanishes and we obtain for the water pressure in the cell:

$$P_1 = \frac{\dfrac{2\rho K}{a^2 \ln\left(\dfrac{a}{r_0}\right)} P_0 - \dfrac{\rho_b K_b P_b}{l h_b} - \dfrac{\rho_b^{'} K_b^{'} P_b^{'}}{l h_b^{'}}}{\dfrac{2\rho K}{a^2 \ln\left(\dfrac{a}{r_o}\right)} - \dfrac{\rho_b K_b}{l h_b} - \dfrac{\rho_b^{'} K_b^{'}}{l h_b^{'}}} \qquad 4$$

The water pressure P_1 in the cell is principally function of the pressure acting on the plugs boundary. P_1 tend to Po if :

$$\begin{cases} \dfrac{\rho_b K_b P_b}{l h_b} = \dfrac{\rho_b^{'} K_b^{'} P_b^{'}}{l h_b^{'}} \\ \dfrac{\rho_b K_b}{l h_b} = \dfrac{\rho_b^{'} K_b^{'}}{l h_b^{'}} \end{cases}$$

In the poroelasticity framework, the water pressure and waterflow are function of the behavior of elastic medium only in the transient state. When steady-state is reached, the rock will remain at rest ($\dot{\varepsilon}_v = 0$) and the physical problem will be only governed by the water flow (purely hydraulic problem).

For example, in the transient state the wall displacement $u(t)$ obeys to the following equation:

$$\frac{u(t)}{a} = \frac{1 + \nu}{E}\left(P_1(t) - P_0\right) \qquad 5$$

Thus when the water pressure in the cell $P_1(t)$ increases, due to the water inflow, the borehole radius will increase. For example with a Young modulus value E = 3800MPa, a Poisson coefficient $\nu = 0.3$, a = 6 cm and a pressure difference equal to 1.5 MPa, the radial displacement is then equal to $3.10^{-3} cm$.

When a solid matrix is described by a viscoplastic behaviour, the hydro-mechanical problem is more complex. It has to be underlined that for a material that exhibits viscoplastic behavior without any threshold, the steady-state can be reached only under the assumption of small deformations. In finite deformation or transformation, the steady-state is reached only when the cavity is totally closed. In fact, when the rock is viscous it will creep under any deviatoric stress and reaches a rest state (so-called asymptotic state) when this one becomes zero, water pressure having no effect on deviatoric stress. More accurate development can be found in Kazmierczak's report (Kazmierczak, 2004) and Cosenza and Ghoreychi works (1999) .

6. Conclusion

The hydraulic and mechanical disturbances induced by a borehole within a viscoplastic argillite have been analysed. On the whole, the numerical results are in good agreement with the measured results, however the measured overpressure of 0.1 MPa has not been reached. This measured overpressure cannot be explained within the framework of poroelasticity unless other transport processes like osmotic effect (not investigated in this paper) are present. Poroelasticity and poroviscoplasticity analyses give interesting results and demonstrate the effect of the creep of the borehole walls. Rock creep could explain the overpressure measured in situ if different creep parameters are used. Numerical results are confirmed by analytical solutions (Cosenza and Ghoreychi, 1999). The same results and trends were found using two different codes: one finite difference code and one finite element code. The small size of the water chamber, the low creep features of the argillites and the permeability of the different materials lead to a hydromechanical problem mainly controlled by water flow.

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